Quantifying the Degree Graduated Elastic Compression Stockings Enhance Venous Emptying☆

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WHAT THIS PAPER ADDS

This paper introduces three methods for measurement of venous return of an elastic stocking. Acute changes in calf volume are a surrogate for changes in venous volume, which can be assessed using air-plethysmography. If a proximal resistance is applied, using incremental pressure with a thigh-cuff, then the ability of a stocking to overcome this force can be quantified by calf volume changes. This may prove to be useful for customising stockings to individual patients based on their ability to increase the venous outflow from the leg.

Objectives: Graduated elastic compression (GEC) stockings reduce reflux and venous volume but their performance on augmenting venous return is unproven. The aim of this study was to quantify the ability of stockings to increase venous outflow from the leg.

Design: A prospective study comparing venous emptying without compression, versus class 1 (18–21 mmHg) and class 2 (23–32 mmHg) compression, using air-plethysmography (APG).

Methods: The right legs of 20 healthy subjects were studied supine. A 12-cm thigh-cuff was inflated in 10 mmHg steps from 0 to 80 mmHg while the corresponding increase in calf volume was recorded using the APG sensor calf-cuff. At the 80 mmHg plateau, the thigh-cuff was released suddenly to measure the unrestricted venous emptying. Venous return was assessed by: (a) identifying the incremental thigh-cuff pressure causing the maximal incremental increase in calf volume (IPMIV); (b) measuring the percentage reduction in calf volume in 1 second following thigh-cuff release — outflow fraction (OF); (c) time to empty 90% of the venous volume — venous emptying time (VET90).

Results: Median and inter-quartile range (IQR) baseline values of IPMIV, OF, and VET90 without compression were 20 mmHg (range: 20–30 mmHg), 44% (39–50%) and 13 seconds (8.8–15.9 seconds), respectively. These improved significantly with all stockings. The application of any stocking raised the median IPMIV by 30 mmHg. The change from a class 2 stocking compared with no stocking versus the change from a class 1 stocking to no stocking had a more pronounced effect ($p < .005$). After sudden thigh-cuff deflation, the venous emptying was 41–45% greater and 9–10 seconds faster with all stockings ($p < .005$).

Conclusions: This is the first study to quantify the venous return of below-knee GEC stockings. Assessments of stockings in augmenting venous return may be of use as a way of optimising compression for individual patients unresponsive to standard conservative treatment.

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INTRODUCTION

Stockings are the universal treatment option for most forms of chronic venous disease. Their efficacy has been proven in the relief of chronic superficial venous disease.[1] They can prevent the recurrence of venous ulceration,[2] and in a meta-analysis they have been demonstrated to significantly reduce the incidence of post-thrombotic syndrome after deep vein thrombosis.[3] Their exact mechanism of action is unclear but the probable explanation is through an improvement in venous return.

The three main ways GEC stockings improve venous return is by reducing venous volume (pooling), reducing reflux (calf-muscle pump after-load), and by augmenting venous outflow from the leg. The former two effects are of very small amount but the latter effect has not been quantified. Studies using air-plethysmography as a way of recording acute volume changes in the calf have demonstrated that

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stockings reduce venous volume and reflux.[4,5] However, methods of assessing the performance in augmenting venous return remain under-researched. An understanding of how stockings improve venous return may facilitate their optimisation for patients.

Incremental proximal thigh compression was used in this study to provide a resistance to venous return so that the performance of a stocking at overcoming this obstruction could be quantified using changes in calf volume. The aim of this study was to record these volume changes in healthy subjects while they were wearing stockings of different compression strengths. The hypothesis was that the elastic recoil properties of a stocking would resist the calf volume increases following incremental thigh-cuff compression and improve the rate of venous emptying following sudden deflation.

METHODS

Study design

This was a prospective pilot study on the right legs of 20 healthy individuals (15 male) who had no clinical evidence of venous disease. They were examined in the supine position. The median age was 37 years (24—73 years). The legs were first assessed without compression and then with a class 1 (18—21 mmHg) and class 2 (23—32 mmHg) below-knee stocking. The appropriate size for each subject was determined after ankle and calf measurements and then selected from measuring charts supplied by the manufacturer (Mediven plus open toe, Bayreuth, Germany).

Calf volume measurements were performed using the APG-1000 apparatus comprising a sensor air-cuff for the calf and an air-pump incorporating a pressure/voltage transducer (ACI Medical LLC, San Marcos, CA, USA). This was calibrated prior to each tracing with a 100 mL syringe of air so that changes in pressure/voltage could be converted into volume (mL).

Incremental proximal thigh-cuff compression was achieved using the VenaPulse pump from the same manufacturer. This was attached to a 12-cm wide thigh-cuff (Hokanson) and has been validated as an effective device in providing sustained compression with an instant release foot pedal for deflation.[6] The electrical output from the APG air pump was fed into the WinDaq apparatus from DataQ. This provides highly sensitive recording and data analysis software from which the changes in calf volume were calculated. The set-up is depicted in Fig. 1.

All subjects who took part in this study were junior doctors or healthcare workers who gave their full informed consent before wearing the stockings. This provided the pilot data required for power calculations on sample size, necessary for regional ethical committee approval for a larger study on patients.

Assessment of venous emptying

The thigh-cuff was inflated in stages commencing at 20 mmHg then in increments of 10 mmHg. The corresponding increases in calf volume were displayed on a running trace. Once a plateau was reached the next

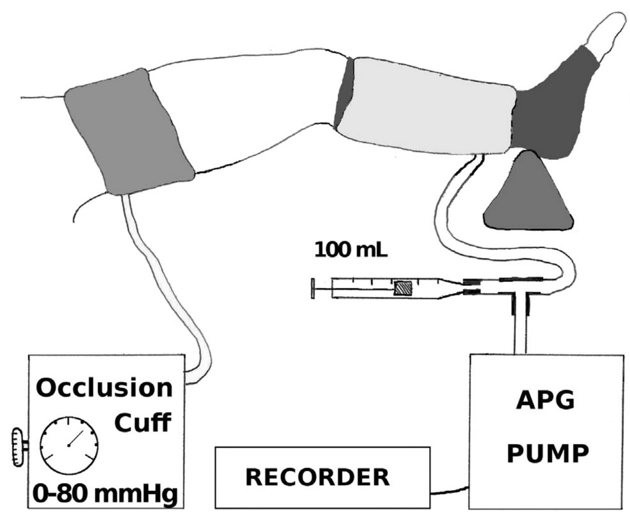

Figure 1. Schematic drawing of the experimental set-up.

inflation step took place. This was indicated on the trace as an event produced by a manual flick of the sensor cuff with the number of flicks corresponding to the pressure. The first step of 10 mmHg was avoided because this pressure was unable to cause a significant increase in calf volume, even without a stocking. At the 80 mmHg plateau the thigh-cuff was deflated suddenly. The resulting release of venous flow was recorded at the calf in order to measure the unrestricted elastic recoil of the stocking.

The effectiveness of a stocking at augmenting the venous return was assessed using three parameters: (a) incremental increase of thigh-cuff pressure causing maximal incremental increase in calf volume (IPMIV); (b) percentage reduction in calf venous volume (VV) in 1 second following sudden thigh-cuff deflation — outflow fraction (OF). OF $=$ volume expelled in 1 second/VV $\times$ 100%; (c) time taken to empty 90% of the VV — venous emptying time (VET90). These parameters are illustrated in a representative inflow and outflow, volume against time, tracing (Fig. 2).

Interface pressures

Stocking interface pressure was measured using the Pico-Press transducer (Microlab Elettronica, Nicolò PD, Italy). In a study that compared three devices it was validated as a reliable instrument for measuring pressure beneath compression devices.[7] It is an inflatable diaphragm with a capacity of 2 mL attached to a hand-held transducer via a thin tube. When placed between the stocking and the leg, approximately 5 cm above and 2 cm posterior to the medial malleolus, it provides feedback on the in vivo compression strength of the stocking.

Data analysis

Tracings were analysed manually on a large screen using the inbuilt precision cursors provided by the WinDaq software and the data were transferred onto a spreadsheet. Statistical analysis was performed using the IBM SPSS statistics package version 19 (IBM Corporation, Armonk, NY, USA).

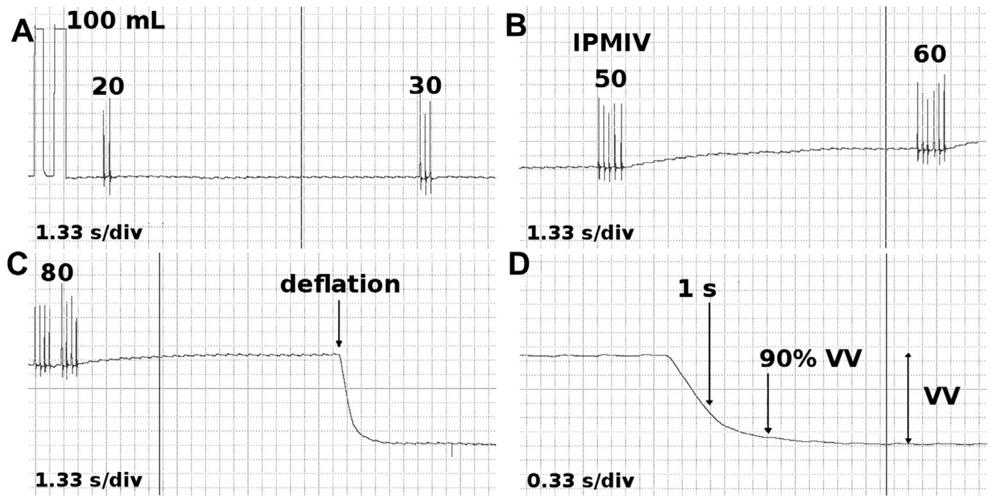

Figure 2. Sections of a continuous graphical tracing in subject wearing a class 1 stocking. The numbers over the event markers represent the thigh-cuff pressure in mmHg. (A) An inflation to 20 mmHg is not met with an increase in calf volume. (B) An inflation from 40 to 50 caused the maximal increase in calf volume, making the IPMIV 50 for this subject. (C) An inflation from 70 to 80 still caused a corresponding increase in calf volume. (D) Points on the outflow curve with the tracing in C expanded from which the OF and VET90 are derived.

Non-parametric statistics were used with medians, interquartile ranges (IQR) and ranges, and charted using boxplots. Outliers are represented by circles and extreme outliers by stars. The Wilcoxon signed rank test was used to test for significance between different stockings versus no stocking. This test was used also to compare the change from no stocking to class 1 versus the change from no stocking to class 2. Change scores were used because they take into account the baseline score for each individual leg, thus allowing direct comparisons between class 1 and class 2 stockings. Correlations between the interface pressures and the IPMIV were performed using the Spearman rho test. Significance was achieved when $p < .05$.

RESULTS

Subject characteristics

The baseline characteristics of the volunteers are shown in Table 1. The legs examined were of similar shape and size as demonstrated by the calf/ankle circumference ratios and stocking sizes. Although the interface pressures beneath the stocking showed great variation, the medians were within the range specified by the manufacturer.

Table 1. Baseline characteristics of the 20 healthy legs (subjects) studied.

	Median	IQR	Range
Age	37	29–48	24–73
Calf/ankle circumference ratio	1.7	1.6–1.7	1.3–1.8
Stocking size	3	2–4	2–3
Class 1 interface (mmHg)	18	12–20	7–27
Class 2 interface (mmHg)	24	19–28	16–34
Venous volume (mL)	84	80–94	56–165
IPMIV	20	20–30	20–30
Outflow fraction[a] (%)	44	39–50	21–62
VET90 (seconds)	13	9–16	4–28

IPMIV = incremental pressure causing maximal increase in calf volume; IQR = inter-quartile range; VET90 = venous emptying time to 90% of the venous volume.

[a] Percentage volume reduction in 1 second after thigh-cuff release.

Venous emptying

A representative graph and results on quantification of venous return are depicted in Figs. 2 and 3, respectively. Stockings significantly reduced the supine venous volume (Fig. 3A), defined as the difference in calf volume at the 80 mmHg thigh-cuff pressure plateau from the baseline achieved after cuff release (Fig. 2D). The threshold thigh-cuff pressure at which the calf volume increased the most was significantly higher with a stocking as shown in Figs. 2B and 3B. This is the point at which the in vivo compression properties of the stocking failed and it started to stretch. The GEC stocking was able to resist the increases in calf volume under the low pressure conditions of the thigh-cuff but "gave way" under higher pressures when it was no longer able to prevent the calf from swelling. As shown in Fig. 3B, the thigh pressure required to restrict venous emptying was 30 mmHg higher with GEC stockings. Interestingly, further increases in thigh-cuff pressure resulted in further increases in calf volume. However, these increases became less with successive inflations. At the inflation step from 70 to 80 mmHg, there was still a corresponding increase in calf volume, although small, indicating that this pressure was not high enough to occlude all veins in a supine patient (Fig. 2C). Presumably, this is because increasing thigh-cuff pressures cause increasing venous obstruction and therefore increasing calf volumes. At the point of venous occlusion, no further increases in calf volume will be expected. Close analysis of the tracing revealed a regular transmitted pulsation corresponding to the subject's heart rate.

At the 80 mmHg plateau the thigh-cuff was suddenly deflated (Fig. 2C). This was expanded on the trace from 1.33 s/division (Fig. 2C) to 0.33 s/division (Fig. 2D) to facilitate analysis of the outflow curve. Generally, the effect of a stocking made the outflow curve steeper. Overall, the outflow fraction was significantly greater (41–45%) and the

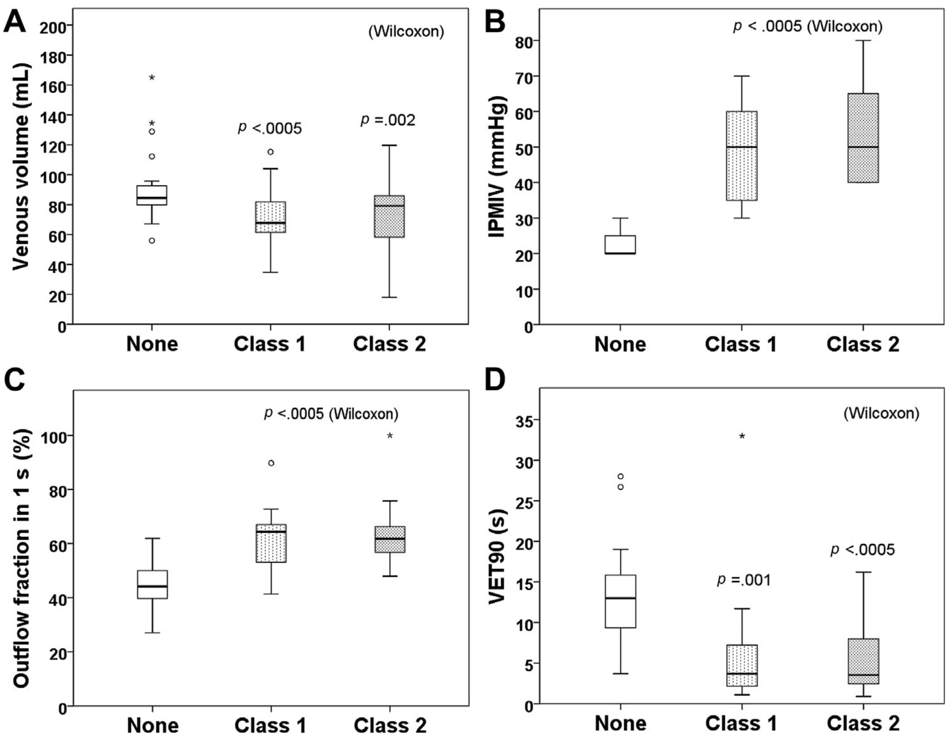

Figure 3. Significant effects of a stocking in 20 normal legs at restricting the supine venous volume (A), the IPMIV (B), the OF (C) and the VET90 in response to proximal obstruction. The *p* values above each box plot represent the statistical significance of each class of stocking versus no stocking.

VET90 was significantly faster (9—10 s) with GEC as shown in Fig. 3C and D, respectively. The median (IQR) baseline values of outflow fraction and VET90 without compression were 44% (39—50%) and 13 seconds (8.8—15.9 seconds), respectively. With a class 1 stocking these improved to 64% (52—67%) and 3.7 seconds (2.1—8 seconds). With a class 2 stocking they improved to 62% (56—67%) and 3.5 seconds (2.3—8 seconds).

It was not possible to demonstrate haemodynamic differences between a class 1 stocking and a class 2 stocking from the outflow curve. However, the median change in IPMIV of 20 mmHg with a class 1 stocking compared with no stocking versus 30 mmHg with a class 2 stocking compared with no stocking was statistically significant (Fig. 4).

Interface correlations

The hypothesis that the stronger the stocking the greater the outflow resistance required to prevent its expansion is supported in Fig. 5. However, the correlation was poor.

DISCUSSION

The sequence of events that underpin this study are as follows. Venous emptying in a supine subject occurs when the combined forces from venous elastic recoil (VER) and the recoil of the stocking are greater than the forces hampering the venous return. The result of these events is reflected in the volume changes in the calf and this can be quantified using APG. Two additional assessment parameters have been introduced, the IPMIV and the VET90. These were used to provide more information on the ability of stockings to increase venous outflow.

Investigations into venous haemodynamics require challenge tests in order to modulate flow so that measurements can be compared in health and disease, and after different treatments, including stockings. A previous study on 26 hospitalised medical patients, while at rest and supine wearing thigh-length GEC stockings, failed to demonstrate any change on popliteal or femoral vein blood velocity, irrespective of whether the patients had venous disease.[8] However, if the venous return is challenged with proximal

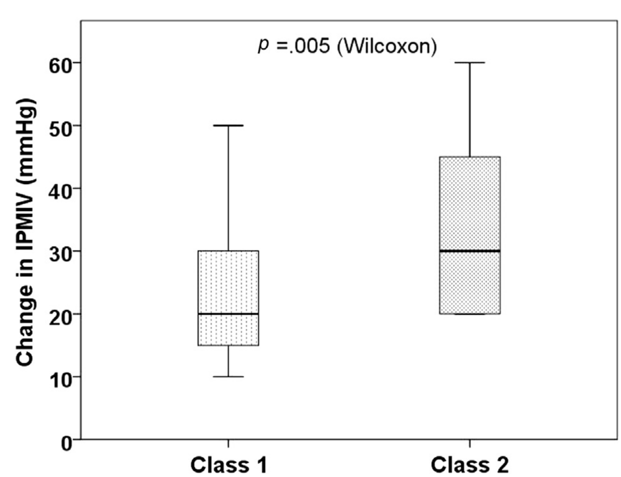

Figure 4. Significant differences between the ability of different stocking strengths to prevent calf volume increases in response to increases in proximal obstruction.

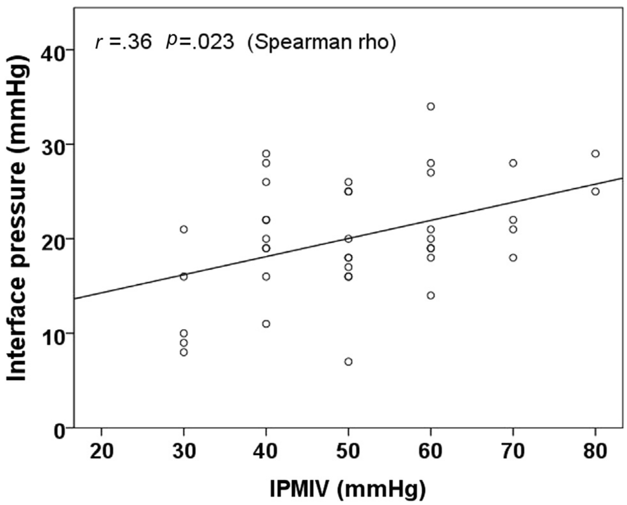

Figure 5. Relationship between stocking interface pressure and the IPMIV.

obstruction/release then differences are observed as the present study has demonstrated.

It is interesting to note that a study which examined the effects of four different brands of compression stockings on venous function in 11 patients was unable to detect a significant difference in the venous volume, venous filling index, or the outflow fraction with stockings.[9] This is surprising and in contrast to the present study which demonstrated significant differences in the venous volume and the outflow fraction in healthy individuals.

Outflow fraction is a common method used to measure outflow resistance and has been shown to be of value in the assessment of deep vein thrombosis,[10] venous claudication,[11] and the post-thrombotic syndrome.[12] As these conditions cause an obstruction to flow, it is understandable why the OF decreases because the blood has to overcome the obstruction. However, venous elastic recoil is also a determinant of outflow. A high venous elasticity would increase the force and volume of ejection after thigh-cuff release and this would increase the outflow fraction. Diseased veins lose their elasticity and therefore outflow fraction assessments are likely to decrease. This principle was realised in two studies which examined the elastic modulus of veins.[13,14] In the absence of proximal disease, outflow fraction may be regarded as a measure of venous elastic recoil. The addition of a stocking will augment the elastic properties of veins. Therefore, in healthy legs the principle determinants of outflow fraction are the combined elastic properties of the veins and the stocking.

The third parameter measured was the venous emptying time, VET90. The value of 90% was used because the shallow termination of the outflow curve makes it difficult to determine the exact time point at which this curve reaches a baseline. This is the same principle as the venous filling time, VFT90, used in the assessment of the venous filling index parameter of APG.[15]

Consideration was given to using the outflow fraction after 4 seconds, as reported in another publication,[16] but this duration was too long to be useful because of the enhanced venous emptying provided by a stocking. For this reason the VET90 was developed and used. Furthermore, the use of the outflow fraction after 1 second as a method of detecting proximal obstruction has been questioned in another publication.[17] That study demonstrated that the first second of outflow relates to the unrestricted filling of the dead space compressed initially by the thigh cuff rather than any impediment to flow further proximal.

This study has demonstrated a significant improvement in venous outflow with GEC stockings. This may have benefit in improving the yield of iliac compression syndromes when using the outflow fraction as a non-invasive diagnostic tool. This is because venous elastic recoil alone may not provide a sufficiently strong flow impulse on thigh-cuff release, especially in post-phlebitic veins. Therefore, outflow fractions obtained by augmenting the venous elastic recoil with a stocking may help in the selection of patients requiring a stent. Furthermore, it may prevent unnecessary invasive tests like CT venography and intra-venous ultrasound in patients suspected of having compression syndromes. The concept of improving venous outflow with compression to facilitate an investigation is a well-established principle in venous diagnosis.[6,18]

Accurate measurements of venous volume are the cornerstone for all measurements derived from the outflow curve. The current study examined healthy subjects in the supine position throughout and used the plateau achieved after 80 mmHg compression as the maximal volume. The baseline of the outflow curve was used as the zero reference point for simplicity in contrast to studies that use either the original baseline before the onset of thigh compression[16] or an estimate between the original and final baselines.[12] This is because the outflow baseline is invariably lower than the baseline at the start as shown by comparing Fig. 2A with Fig. 2D. The reason for this may be because thigh compression results in the buildup of veno-active metabolites and opening up of the drainage pathways from the backpressure. It also induces reactive hyperaemia, which increases arterial inflow and thus venous outflow.[19]

The poor correlation observed with stocking interface pressure and the IPMIV may be related to two factors. Firstly, interface pressure measurements on legs of different shapes and sizes are variable[20] and depend on the exact placement of the sensor diaphragm.[21,22] If it is too close to the fulcrum points of a tendon or bone, then high readings are expected. Conversely, placement within the valley between these prominences will result in low readings. Secondly, the thigh-cuff inflation steps may have been too great because the differences in stocking strengths were less than 10 mmHg. Repeating the experiment using steps of 5 mmHg may have improved the correlation.

The performance of a stocking at reducing calf volume and reflux has been investigated recently in patients with post-thrombotic syndrome.[23] That study reported significant reductions in the venous volume and the venous filling index. Once a global index of stocking performance can be measured, then it may provide a way of selecting stockings based on their overall haemodynamic characteristics. Future work is required to complement these previous assessments on venous volume and venous filling index with the current assessment of the ability of stockings to increase the venous return in patients.

Study limitations

This study has introduced the IPMIV, VET90, and the outflow fraction as a way of measuring venous and stocking recoil (venous emptying). Significant artefacts and confounding variables have not yet been identified from using these measurements.

A further point relates to the practical importance of this study. Subjects were examined in the supine position, but the effect of compression is necessary in the standing position. It could be possible that what is so clear in the supine position is much less clear in the standing position, especially with a GEC stocking producing a very low pressure. This study is a first step in assessing venous emptying in subjects supine and at rest. Detailed assessments in patients standing and walking will be necessary to expand on our proof-of-concept study and to determine the full clinical significance of this work.

CONCLUSION

This is the first study to demonstrate that graduated elastic compression stockings significantly improve venous return in normal subjects as measured using two novel parameters, the IPMIV and the VET90, as well as the outflow fraction. Plethysmographic assessment on venous emptying should complement evaluations on controlling reflux and volume to provide an overall index on the haemodynamic performance of a stocking. This may be of benefit in customising stockings for individual patients, which may result in clinical improvements.

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CONFLICT OF INTEREST

None.

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